ROBUST SEMI-ACTIVE RIDE CONTROL UNDER STOCHASTIC EXCITATION

Jeremy Kolansky- Virginia Tech
Amandeep Singh, Jill Goryca- US Army TARDEC

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Outline

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- Vehicle Modeling
- Road Profile and Stochastic Excitation
- Performance Metrics
- Control Methodology
- Simulation Results
  - Robust for parameter range
  - Robust for unknown input
  - Comparison
- Conclusions

Introduction/Overview

Ride comfort for military vehicles are important for several reasons:

1) **Fatigue caused by vehicle vibrations**
2) **Motion sickness reduction by smoothed vehicle motions**
3) **Ability to modify handing conditions based upon terrain**

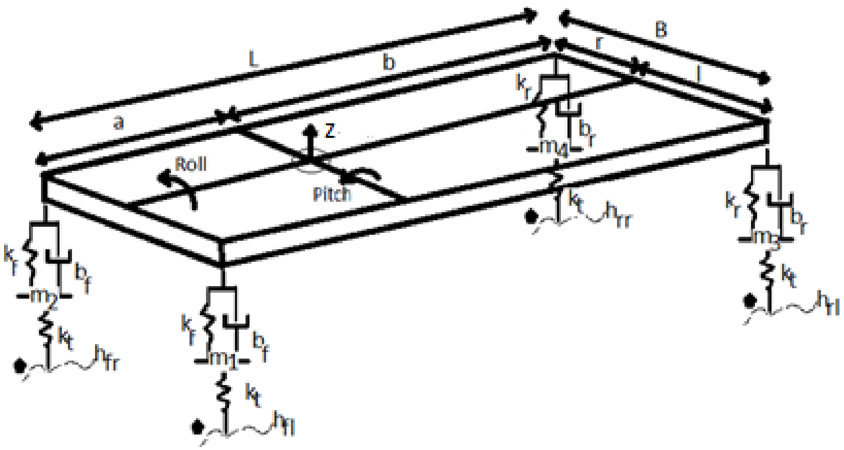
Suspension Type:

1) **Fully Active Suspension**
2) **Passive Suspension**
3) **Semi-Active Suspension**

Control Method:

1) **LQR/H-Infinity/Linear Methods**
2) **Nonlinear/Adaptive**
3) **Discontinuous (Parameterized or otherwise)**

Seven Degree of Freedom Vehicle Model



Suspension Forces

$$F_{fl} = k_{fl}(z - a\,\theta + l\phi - z_{fl}) + c_{fl}(\dot{z} - a\dot{\theta} + l\dot{\phi} - \dot{z}_{fl}) \quad (1)$$

$$F_{fr} = k_{fr}(z - a\,\theta - r\phi - z_{fr}) + c_{fr}(\dot{z} - a\dot{\theta} - r\dot{\phi} - \dot{z}_{fr}) \quad (2)$$

$$F_{rl} = k_{rl}(z + b\,\theta + l\phi - z_{rl}) + c_{rl}(\dot{z} + b\dot{\theta} + l\dot{\phi} - \dot{z}_{rl}) \quad (3)$$

$$F_{rr} = k_{rr}(z + b\,\theta - r\phi - z_{rr}) + c_{rr}(\dot{z} + b\dot{\theta} - r\dot{\phi} - \dot{z}_{rr}) \quad (4)$$

Wheel Dynamics

$$\ddot{z}_{fl} = \frac{-k_{u,fl} * (z_{fl} - z_{g,fl})H(z_{g,fl} - z_{fl}) + F_{fl}}{m_{fl}} - g \quad (5)$$

$$\ddot{z}_{fr} = \frac{-k_{u,fr} * (z_{fr} - z_{g,fr})H(z_{g,fr} - z_{fr}) + F_{fr}}{m_{fr}} - g \quad (6)$$

$$\ddot{z}_{rl} = \frac{-k_{u,rl} * (z_{rl} - z_{g,rl})H(z_{g,rl} - z_{rl}) + F_{rl}}{m_{rl}} - g \quad (7)$$

$$\ddot{z}_{rr} = \frac{-k_{u,rr} * (z_{rr} - z_{g,rr})H(z_{g,rr} - z_{rr}) + F_{rr}}{m_{rr}} - g \quad (8)$$

Vehicle Body Dynamics

$$\ddot{z} = \frac{-(F_{fl} + F_{fr} + F_{rl} + F_{rr})}{mass} - g \quad (9)$$

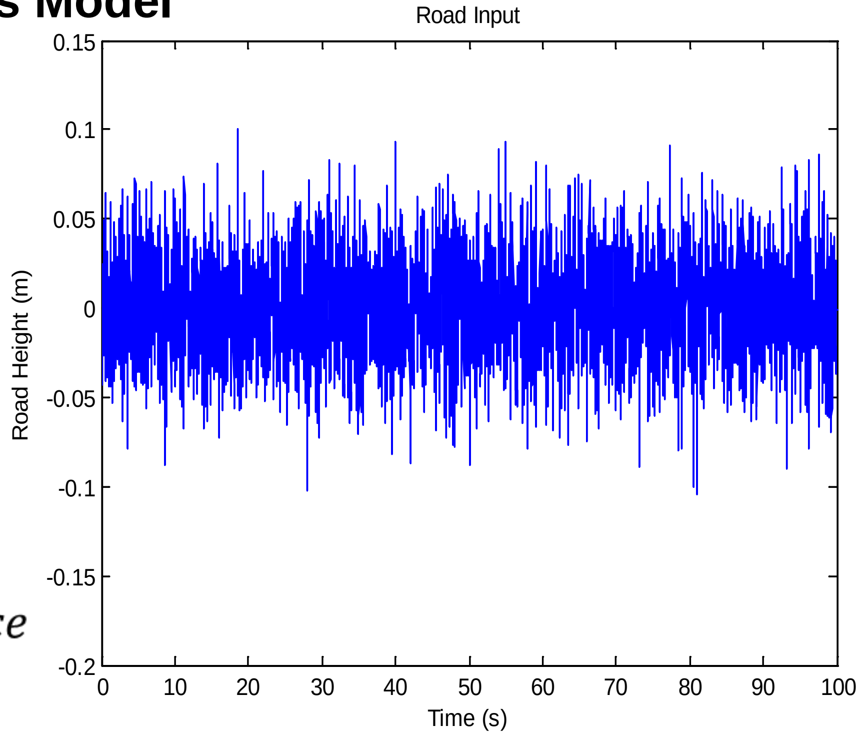
$$\ddot{\theta} = \frac{a(F_{fl} + F_{fr}) - b(F_{rl} + F_{rr})}{J_{Pitch}} \quad (10)$$

$$\ddot{\phi} = \frac{-l(F_{fl} + F_{rl}) + r(F_{fr} + F_{rr})}{J_{Roll}} \quad (11)$$

Road Profile and Stochastic Representation

Third Order Auto Regressive Time-Series Model

$$u_i = \phi_1 u_{i-1} + \phi_2 u_{i-2} + \phi_3 u_{i-3} + \varepsilon_i \qquad (12)$$



Feedback Coefficients

$$\phi_1 = 1.2456,$$
$$\phi_2 = -0.2976,$$
$$\phi_3 = -0.1954,$$
$$\varepsilon_i = Gaussian\ White\ Noise, Unity\ Variance$$

A series of statistical tests were conducted to examine the validity of the time-series model representation of the road profile

Road Profile and Stochastic Excitation

Third Order Auto Regressive Model

$$u_i = \phi_1 u_{i-1} + \phi_2 u_{i-2} + \phi_3 u_{i-3} + \varepsilon_i \tag{12}$$

Front-Left-Wheel: $\mathrm{z_{wfl}(t)} = z_r(t) = u_i$

Front-Right-Wheel: $z_{wfr}(t) = z_r(t+\delta) = u_{i+\delta}$

Rear-Left-Wheel: $z_{wrl}(t) = z_r\left(t + \frac{L}{v_s}\right) = u_{i+\frac{L}{v_s}}$

Rear-Right-Wheel: $z_{wrr}(t) = z_r(t + \frac{L}{v_s} + \delta) = u_{i+\frac{L}{v_s}+\delta}$

Wheelbase: L Vehicle Speed: v_s Delay: δ

Performance Metrics

- **Absorbed Power (At the seat locations)**
  - Next Slide
- **RMS Acceleration (At the seat locations)**
  - $\sqrt{\ddot{z}/N}$
- **Road Holding (At each wheel)**
  - $z_{wheel} - z_{road}$
- **Rattle Space (For each suspension strut)**
  - $z_{body} - z_{wheel}$

Performance Metrics – Absorbed Power

- **Absorbed Power**
  - Measure of ride comfort
  - Amount of energy absorbed from ride vibration

$$\overline{AP} = \lim_{T \to \infty} \frac{1}{T} \int_0^T F(t)V(t)dt$$

- Actual absorbed power with physical characteristics
- Typical coefficients of a 50th percentile man are used
- For the 7-DOF model, the absorbed power is computed at all the four seats (two in front and two in rear), and averaged to represent a single ride comfort metric used for the study.

Control Methodology – Accelerometer Driven Damper (ADD)

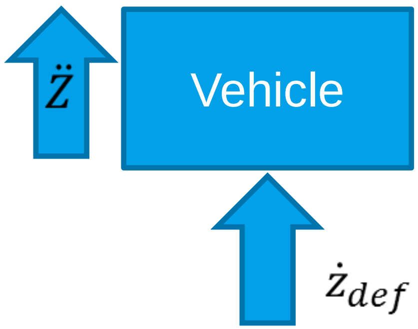
Infinite Control Authority ADD

$$C_{desired} = C_{min} + H(\ddot{z}\dot{z}_{def})(C_{max} - C_{min}) \quad (13)$$

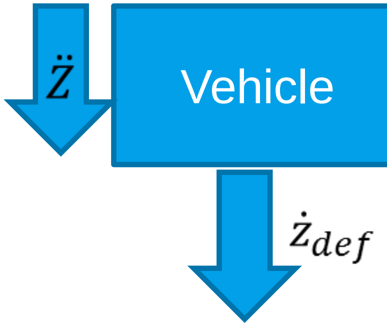
Moving Average Filter

$$Z_k = \sum_{i=0}^{N} \frac{1}{N+1} z_{K-i} \quad (14)$$

Case 4



Case 1



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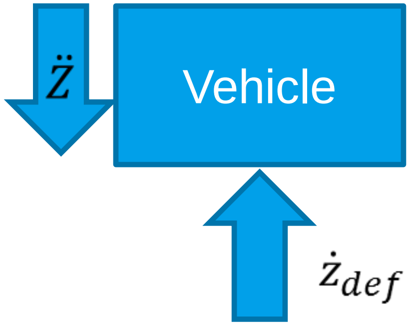
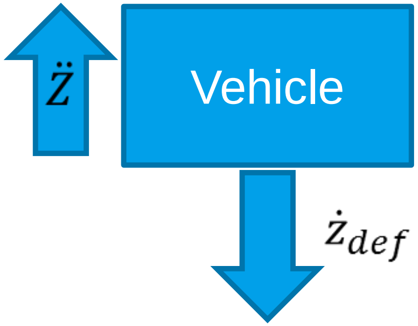
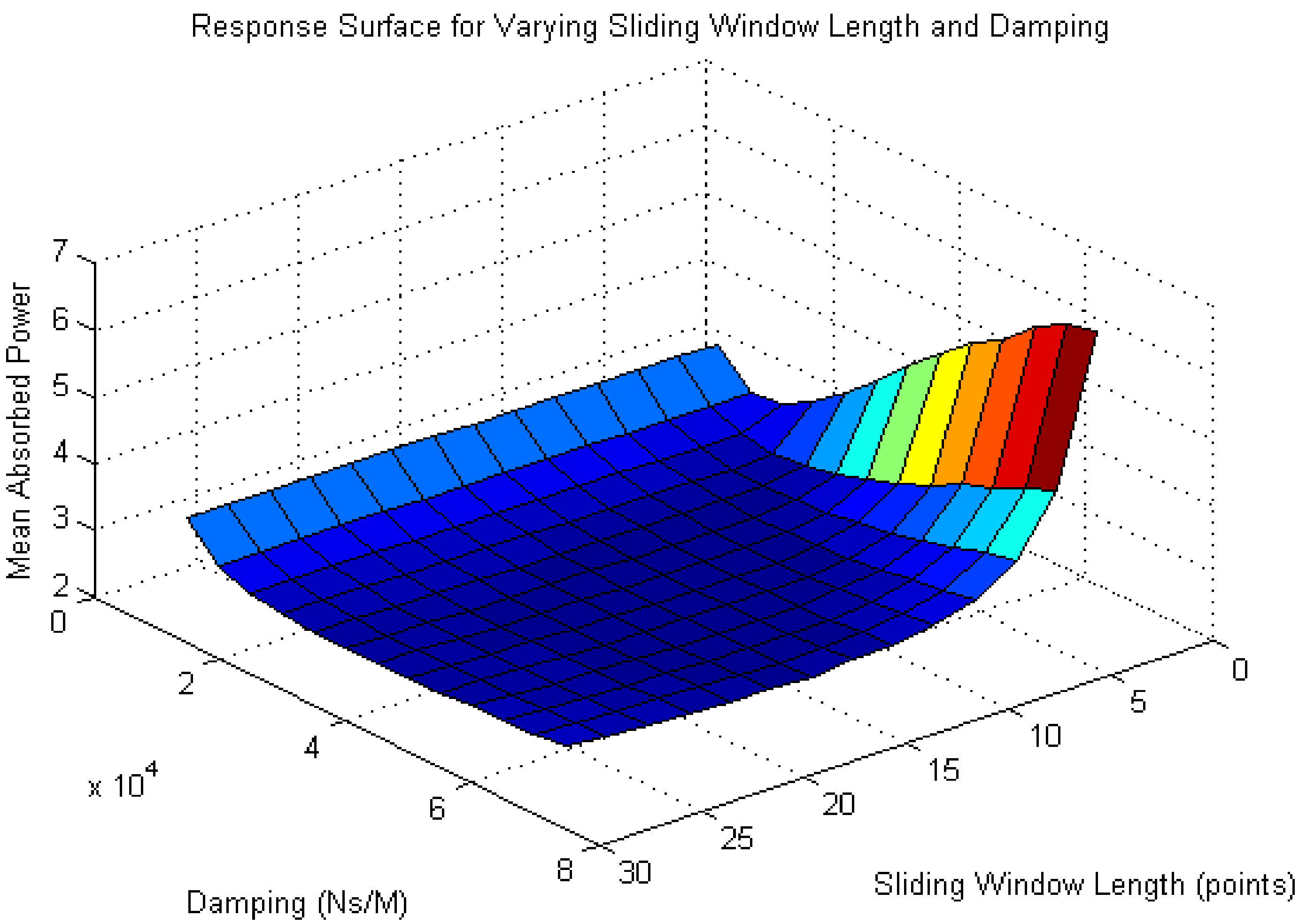


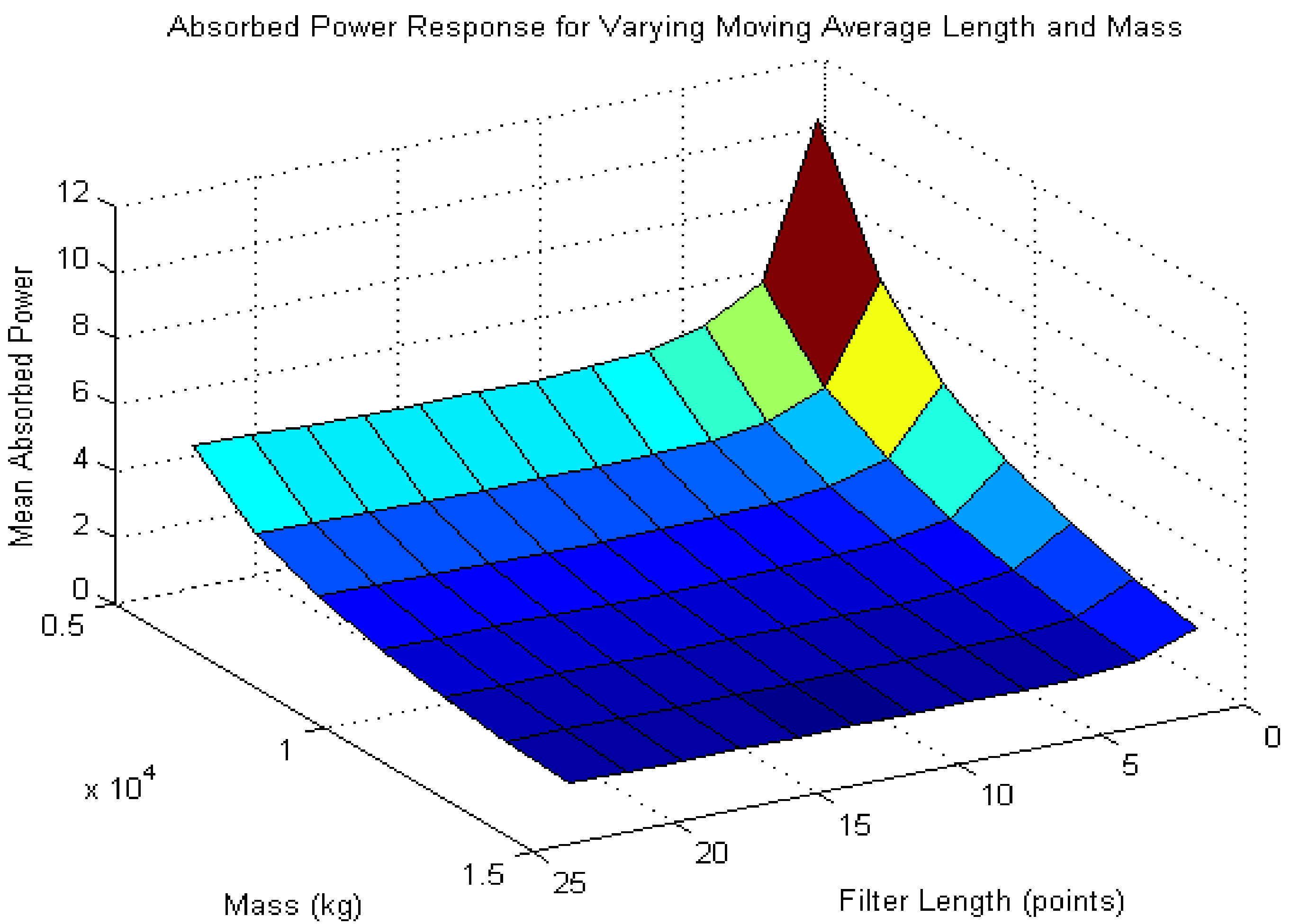
Case 3



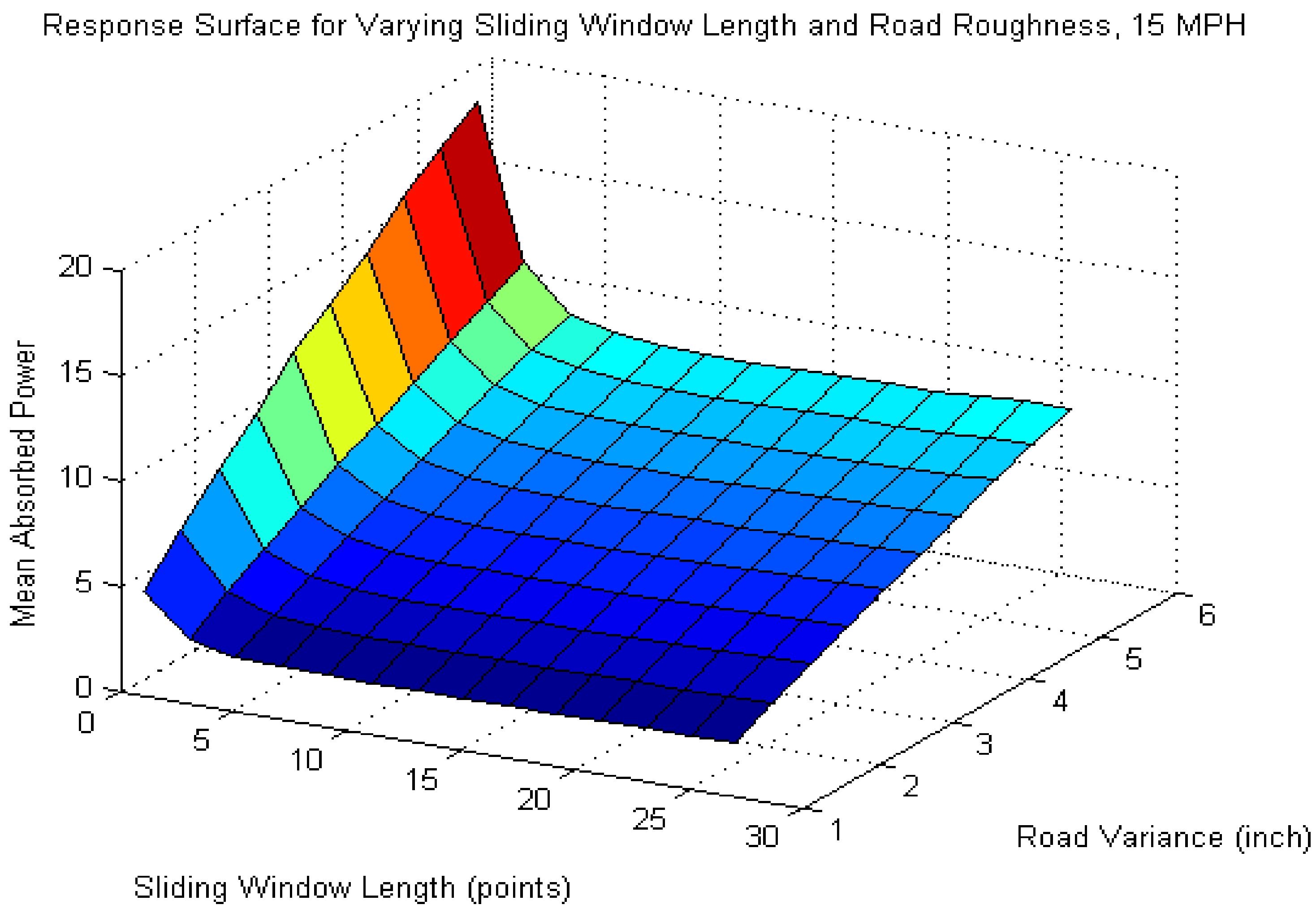
Simulation Results – Parameter Effects



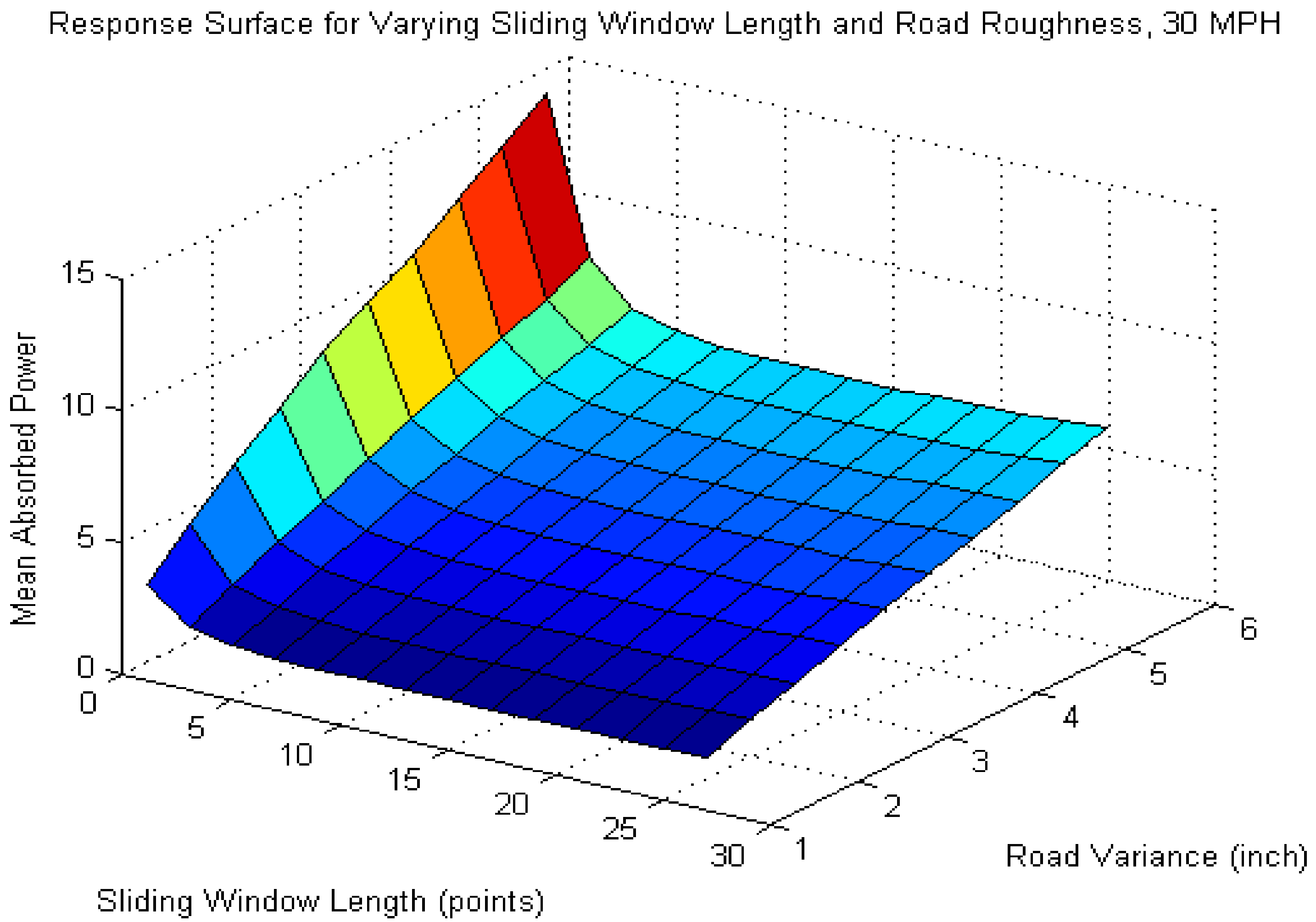
Simulation Results – Parameter Effects



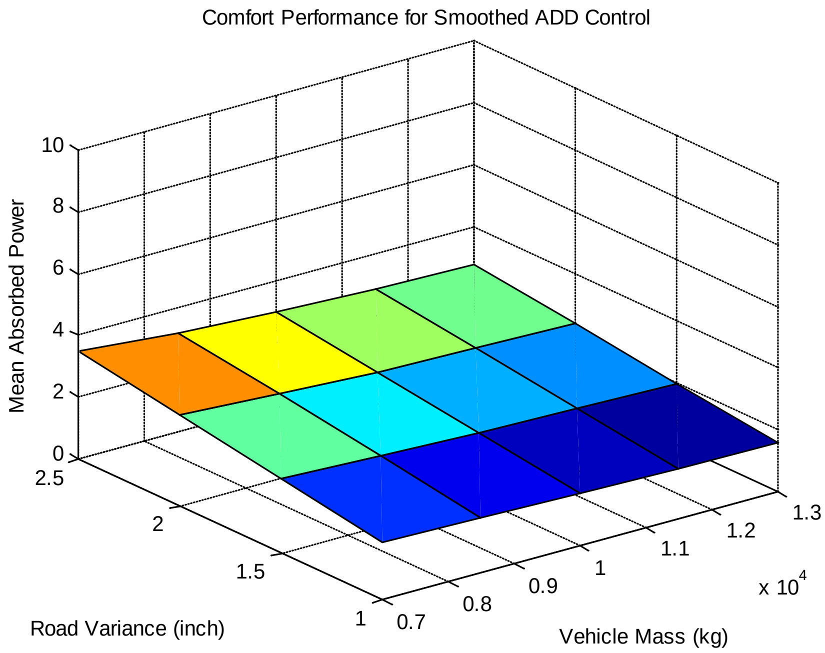
Simulation Results – Stochastic Road Effects

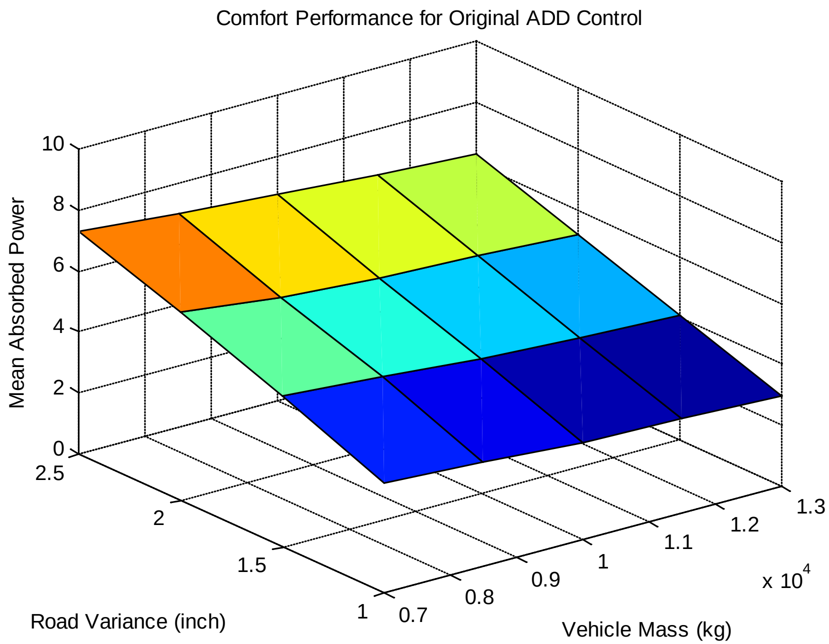


Simulation Results – Stochastic Road Effects



Simulation Results – Ride Comfort Comparison





Quarter Car Results	Average Absorbed Power (W)	Sprung Mass Acceleration RMS (g's)	Road Holding Max (in)
Passive	26.65	0.61	4.45
SH 2-state	6.19	0.39	4.87
SH-ADD	3.43	0.25	4.87
SH Linear	3.05	0.23	5.54
ADD	1.28	0.19	5.11
Smoothed ADD (Proposed)	1.09	0.17	5.18

Conclusions

- Smoothing function significantly improves over the original ADD control for the higher fidelity models than just quarter car models.
- Invariant with respect to vehicle mass/inertia (Does not require any vehicle parameters)
- Invariant with respect to road profile
- Computationally efficient algorithm. Challenge comes from sensor implementation